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Design Criteria for Rapid-Response Pneumatic Monitoring Systems

By Charles D. Litton

UNITED STATES DEPARTMENT OF THE INTERIOR

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ILLUSTRATIONS

DESIGN CRITERIA FOR RAPID-RESPONSE PNEUMATIC MONITORING SYSTEMS

By Charles D. Litton [1]

ABSTRACT

This Bureau of Mines report presents a discussion of the essential components of pneumatic monitoring systems and their associated functions. Design criteria are presented which can be used for the design and fabrication of pneumatic monitoring systems having total system response times on the order of 15 to 30 min. To illustrate the utility of these design criteria, two detailed design examples are presented.

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INTRODUCTION

Improving the degree of safety afforded underground mine personnel is a major goal of the Bureau of Mines' research program. This report discusses in detail a methodology for monitoring of mine air contaminants that has the potential to improve underground mine safety by providing early warning of developing hazards. The data on which this report is based was acquired from both in-house research projects and contractual efforts originating from the Fires and Explosions Group of the Pittsburgh Research Center, Bureau of Mines.

Many potential hazards in underground mines are preceded by, or result in, the formation of contaminants that are carried throughout the mine by the imposed ventilation. Continuous monitoring of the mine air for contaminants has the potential to provide early warning of associated hazards in a time sufficient to successfully initiate control measures and to ensure the safety of underground personnel.

Two techniques exist for continuous monitoring of the mine air. The first technique (called the electronic method) consists of placing one or more contaminant sensors (called sensor packages) at carefully chosen locations within an underground mine. These sensor packages are then hard-wired to a remote station that provides electrical power for the sensors and accepts electrical signals from the sensors. The remote station may also contain a multiplexing function by which sensor signals are transmitted via two-conductor communication lines to a central, master control center. Depending upon the size of the mine and the number of sensor packages, this method can be relatively simple (for instance, one sensor package with a remote station that also serves as the master control center); or it can be complex (for instance, several sensor packages with several remote stations controlled by a master control center). For this technique, every underground monitoring point has a sensor package containing one or more sensors.

In the second technique (called the pneumatic method), sensor packages are replaced by tubes. For every underground monitoring location, a tube extends from that location to a central control station. At this control station, pumps continuously pull samples of mine air from the monitoring locations through the tubes and then exhaust the samples into one or more contaminant sensors. Sensor outputs can be recorded and displayed at this station, or the outputs can be multiplexed to a master control center for recording and display.

The pneumatic method has been used successfully for continuous monitoring applications where the rate of development of a particular hazard is slow with respect to the overall response time of the system. Such applications would include the continuous monitoring for detection of spontaneous combustion and for assessing the status of underground sealed fire areas.[2] It has been argued, and quite erroneously, that imposed time delays due to tube transit times and sequencing times are unacceptable for applications where the rate of development of a particular hazard can be quite rapid.

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[2]Burgess, D., and H. Hayden. A Carbon Monoxide Index Monitoring System in an Underground Coal Mine. Soc. Min. Eng., AIME, Ann. Fall Meeting, Salt Lake City, Utah, September 1975, SME Preprint 75-F-350, 25 pp.

Chamberlain, E. A. C., and D. A. Hall. The Practical Early Detection of Spontaneous Combustion. Colliery Guardian, London, May 1973, pp. 190-194.

Dalverny, L. E., Z. J. Fink, and J. P. Weinheimer. Continuous Gas Monitoring Using Tube Bundles at the Joanne Mine Fire. BuMines TPR 92, 1975, 12 pp.

While it is true that these times can be significant, it is also true that they can be dealt with quantitatively so that their effects can be minimized. Further, by presenting design criteria, primarily with respect to these time constraints, it becomes possible to calculate, in advance, the overall time response of a pneumatic monitoring system. And this information can subsequently be used to determine if a pneumatic monitoring system can be designed to meet the monitoring requirements for a proposed application.

It is the intent of this report to describe the components necessary for fabrication of a pneumatic monitoring system and to present, in detail, design criteria that can be used to assess the limiting time responses of such systems. In so doing, it becomes apparent that, through prudent engineering design, pneumatic monitoring systems can be used to monitor for hazards that develop quite rapidly.

GENERAL DESCRIPTION

A pneumatic monitoring system can be considered to be composed of two major elements. First, there is a set of two or more tubes extending from a central control station to the monitoring locations. These tubes are used to convey air samples from the monitoring locations to the control station where various contaminant levels are determined. Second, there is the central control station where pumps continuously purge the sampling tubes and present the air samples to the contaminant sensors for measurement. These two elements, and their components, will now be discussed in some detail.

THE TUBING SYSTEM

The set of tubes used for conveying air samples is commonly in the form of a bundle of tubes (hence, the name "tube bundles"), although for rapid-response systems, single tubing of >0.635-cm ID(>1/4-in-ID) may often be required. Commercially available tube bundles consist of two or more tubes per bundle with each tube within a bundle having either an 0.427-cm ID(~1/6-in-ID) or an 0.635-cm ID (1/4-in-ID). The number of tubes per bundle ranges from 2 to 37 for the smaller size tubing, and from 2 to 19 for the larger size. Individual tubes are usually of polyethylene, although metal tubing may also be available from some manufacturers. Each bundle is covered by an outer sheath of polyethylene (~1/8- to 1/4-in thick), which serves to protect the enclosed tubing. Bundles are generally in the form of reels, resembling reels of multiconductor electrical cable. Single tubing is also usually made of polyethylene; other tubing materials are generally available, but at somewhat higher cost.

Any single tube forms a path of communication between the monitoring location and the control station. Air samples must flow through a tube unaltered so that a contaminant measurement is truly indicative of the actual levels at the monitoring location. This constraint implies that some consideration should be given to the potential reactivity of contaminants during tube transport, either with the tube or with other gases in the air sample. In general, contaminants of interest, such as methane, CO, CO_2, or smoke particles, are nonreactive and can be safely transported through polyethylene tubing. On the other hand, sulfur-containing contaminants, such as H_2S or SO_2, tend to react with either water vapor or condensed water during transport. Oxides of nitrogen can react with the polyethylene; if these gases are to be monitored, tubing made of nonreactive materials would be recommended. The more stable gases, nitrogen and oxygen, are nonreactive and can be safely transported through polyethylene tubing.

In addition to the tubing, certain other components are generally required or recommended. At the sampling location, end-of-line dust filters should usually be attached to the sampling tubes to prevent accumulation of dusts within the tubes; this can sometimes result in clogging of the sample tubes. These filters are generally of large surface area and provide little resistance to the flow.

If a tube bundle is used containing four or more tubes, it is generally recommended that connections between tube bundles be protected by a junction box. A junction box is simply a rectangular box, made of heavy-duty metal or plastic, that can be mounted on the ribs of an entry. The lid of the junction box is easily removed, and tube bundles, one coming into the box from either side, can be connected and the lid replaced. The tube bundles entering the junction box are held firmly in place by brackets so that no tension is exerted on the connectors themselves. For bundles containing fewer than three tubes, or for single tubing, it is recommended that, where connections are to be made, the tubing be firmly secured to the rib or roof on either side of the connection so that no tension is exerted on the connection. Once the connection is made, it should be wrapped with heavy-duty tape.

Depending upon the location of the monitoring points relative to the control station, temperature differences along the path of a sampling tube may be encountered; this can result in condensation of water within the tubes.

While water condensation within a tube generally will not affect the performance of the system, the transport of water into the contaminant sensors can significantly affect their performance. For this reason, water traps are usually inserted in the sampling line at the control station just prior to the tube connection to the solenoid valves (use described below).

In some applications, the gas sample may be flammable, and while no energy is available along the tube length to ignite such a flammable mixture, ignition could occur at the control station where power is supplied to the system. If ignition were to occur at this point, it is conceivable that flame propagation back through a sample tube could occur; this potentially could ignite a flammable gas mixture in the vicinity of the monitoring location. To avoid this potential problem, simple in-line flame arrestors should be inserted in the sampling lines between the water traps and solenoid valves. It should be noted that no such occurrences have ever been observed, and these devices are recommended primarily as a precautionary measure.

For applications where pneumatic monitoring systems are to be designed for rapid response (see following sections), it is generally required that all sampling tubes have the same volumetric flow rate through them. For this reason, such systems should have manual valves inserted in the sampling lines between the flame arrestor and the solenoid valves. These valves can then be used for obtaining the proper flow rate through each tube in the system. Such valves can be in the form of "needle" valves or "ball" valves; in most cases, the latter will suffice.

If a sampling tube were fitted with all of these auxiliary components, then from the monitoring location up to the three-way solenoid valves, these components should be installed as per figure 1. Note that these components, except for dust filter and junction box, can be installed at the control station.

THE CONTROL STATION

The control station is literally the heart of a pneumatic monitoring system. It is at this station that pumps continuously purge all of the sampling tubes, with each tube sequentially connected in a regular, repeating fashion to the contaminant sensors. A generalized, pneumatic monitoring system is depicted in figure 2.

Sampling tubes entering the control station are connected to the input ports of three-way solenoid valves (or their equivalent). Multiport rotary valves are available that can accomodate 12 to 24 incoming tubes. For systems using 12 or more sampling tubes, these valves can be used in the place of individual solenoid valves and at a reduced cost. One output port of each solenoid valve is connected to a large scavenger pump, while the second output port is connected to a smaller, sample pump. Typically, the scavenger pump continuously purges all of the sampling tubes, except for one, which is connected through the valving to the sampling pump. Each solenoid valve is energized in a regular, repeating fashion by a combination timer-controller (see figure 3) so that the contaminant levels within each tube can be determined.

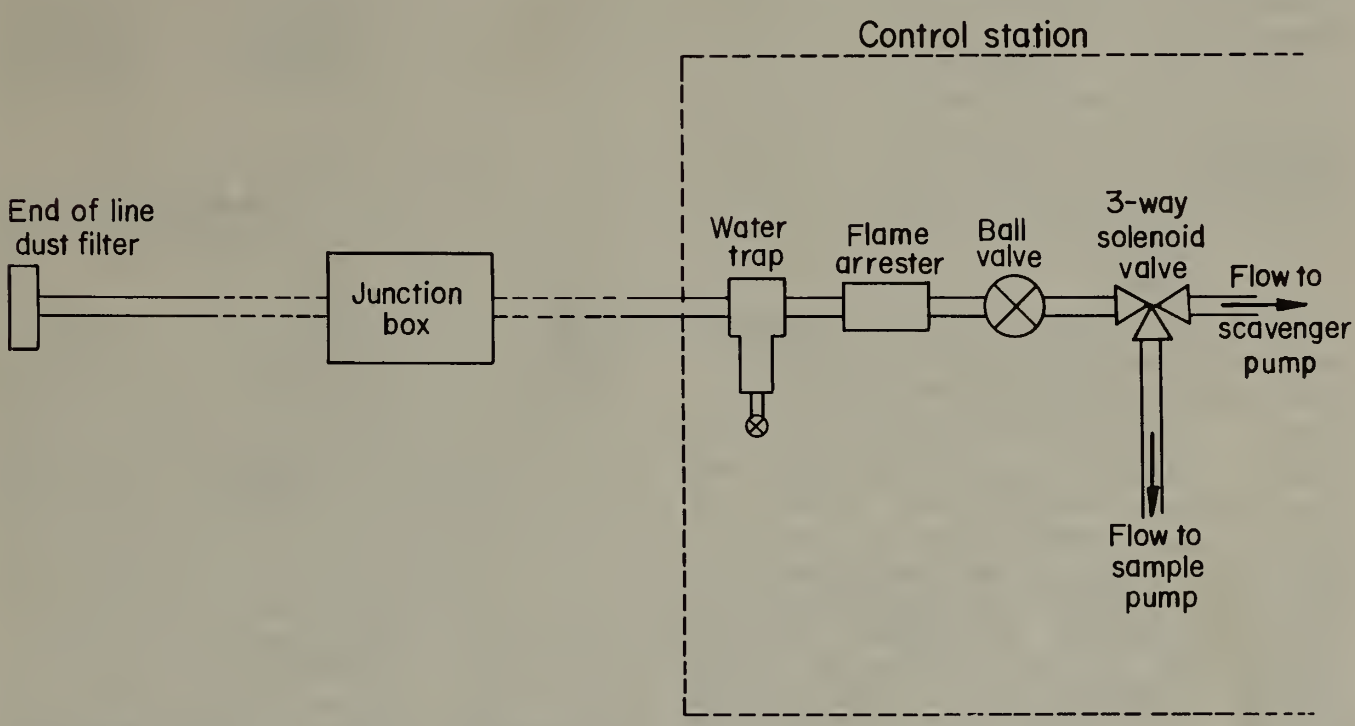

FIGURE 1. - Schematic showing appropriate locations for auxiliary components along the length of a sampling tube. Not all components are required for each system.

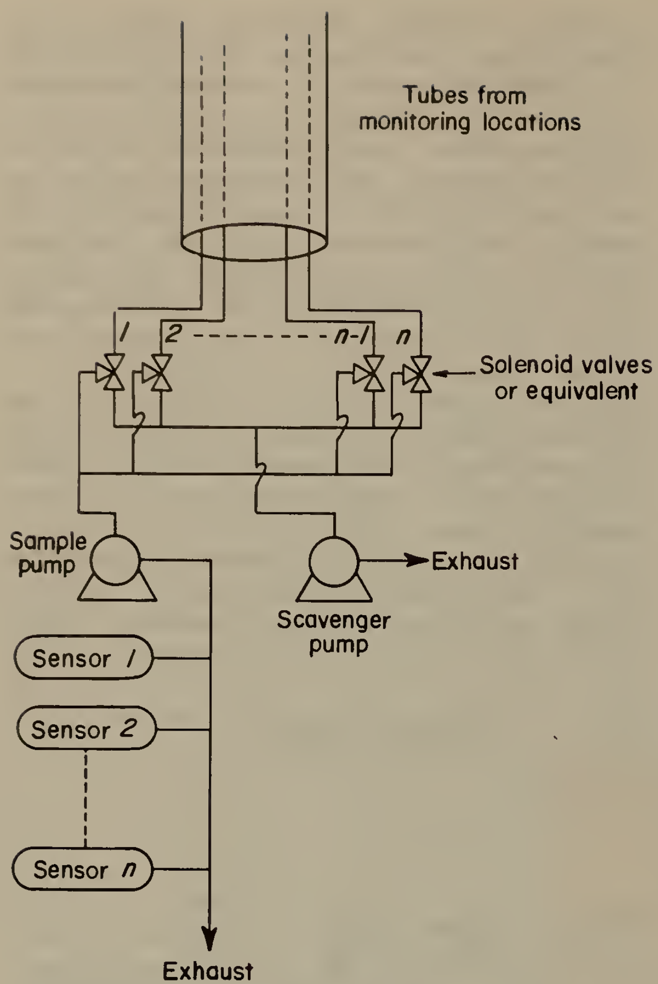

FIGURE 2. - Generalized schematic of a pneumatic monitoring system showing the essential air sampling components at the control station.

Once a solenoid valve is energized, the flow from that sampling tube is diverted to the sample pump, which in turn provides flow to the contaminant sensors, as shown in figure 2. The number and type of sensors required will depend upon the requirements of the monitoring system and the information it is intended to provide. It is worth noting that, for this type of system, many contaminants can be measured at a single convenient location if so desired.

Again, care should be taken in order to avoid any degradation of the air sample by components within the system. Pumps with nonreactive internal components are usually available and are generally recommended for this type of system. Similar consideration should be given to any component that is in direct contact with the air sample.

In order for the control station to operate properly, it must contain electronic functions. These functions are depicted in block form in figure 3. The combination timer-controller is used to provide power to the individual solenoids. In general, the timer is set so that a single tube is sampled for a certain period of time. At the end of that time interval, the timer generates a

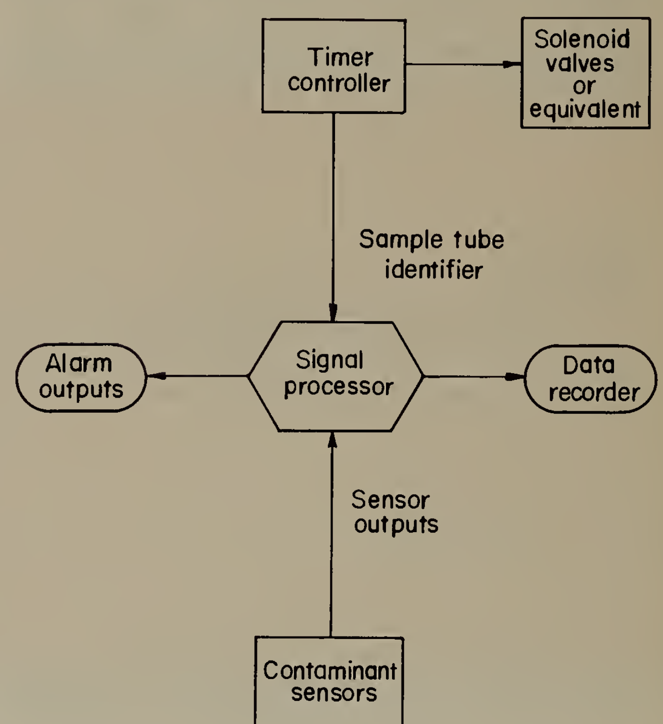

FIGURE 3. - Block diagram showing the electronic functions required for a pneumatic monitoring system.

pulse that is received by the controller. The controller in turn produces a relay closure for the next solenoid valve, and so on. The timer-controller unit also produces a second output, which indicates the current tube whose sample is being sent to the sensors. This output, along with the outputs from the sensors, is connected to a signal processor.

The signal processor in turn provides for alarm outputs and also for input to some type of data recorder, such as a strip-chart recorder. If remote alarms and remote data recording are required, the signal processor can also contain multiplexing and telemetry functions. This unit can be very simple (such as providing for alarms when contaminant levels exceed some value) or it can be more complex (such as providing for data recording and multiplexing or telemetry functions). In general, the signal processor should indicate the tube number associated with the alarm or data output.

If desired, the signal processor can be used to provide information on the operational status of the system. It can contain electronics that, for instance, supervise the sensors and other electronic functions and provide indication of system malfunction. Tube integrity can also be monitored by inserting an electronic flowmeter in the line connecting the solenoid valves to the sample pump. This device can in turn be connected to the signal processor. Since all sampling tubes are required to have the same approximate flow, a low-flow indicator would signal that the tube is being blocked while a high-flow indicator would signal that a tube has been broken.

Again, the number of electronic components and their complexity will depend upon the system requirements.

This section has discussed the operation of a generalized pneumatic monitoring system and the components required to make such a system operational. In principle, this information is sufficient to fabricate a pneumatic monitoring system. However, in order to design a system with a known response time, it is important that the various parameters that determine the overall system response time be discussed.

TIME CONSIDERATIONS

A continuous monitoring system is intended to provide certain specific information that can be used to signal the development of a potential hazard. For a monitoring system to function properly, it must be capable of providing this information in a time sufficient to successfully initiate control measures and to ensure the safety of underground personnel. Consequently, a monitoring system designed to protect against some hazard must have a maximum response time that is less than the anticipated development time of that hazard.

If the hazard development time is τ_m and the maximum system response time is τ_s, then

$$\tau_s < \tau_m \tag{1}$$

if the system is to achieve its intended purpose. When some contaminant is released into the mine air, that contaminant is carried downstream at the ventilation velocity, v_f. If the monitoring location is some distance, ℓ, from the point of origin of the contaminant, then the time necessary for the contaminant to

reach the monitoring location, τ_t, is given by

$$\tau_t = \ell/v_f \tag{2}$$

Now, for a pneumatic monitoring system, once the contaminant reaches the monitoring location, it must travel through a tube of some length, ℓ_o, before it reaches the contaminant sensor. Provided that the pumps have sufficient capacity, the traveltime, τ_ℓ, for laminar flow (Reynolds number < 1,800) through a tube of length, ℓ_o, in meters, and inside diameter, d_o, in centimeters, is given by

$$\tau_\ell > 0.35\ \ell_o d_o. \tag{3}$$

Since all sampling tubes within the system should have the same volumetric flow rate, the maximum tube traveltime will occur for the longest sampling tube in the system.

Once the contaminant reaches the central station, the maximum amount of time that it will take before the contaminant is detected will be one complete sequencing time, τ_{SEQ}. This results from the fact that this particular tube may have been sampled just prior to the contaminant's reaching the central station, and should this happen, then the remaining tubes will be sampled before the contaminant-bearing tube is sampled again. If the sample time per tube is τ_{SAMP}, then the total time to sequence through the tubes is

$$\tau_{SEQ} = n\ \tau_{SAMP} \tag{4}$$

where n is the number of tubes in the system.

The sum of these three times, (eqs. 2-4) is the maximum response time of the pneumatic monitoring system; that is,

$$\tau_s = \ell/v_f + 0.35\ \ell_o d_o + n\ \tau_{SAMP} \tag{5}$$

and this time must satisfy equation 1 when used to monitor for a hazard that has a development time, τ_m. These three times will now be considered in detail.

CONTAMINANT TRANSPORT TIME, τ_t

The transport time, τ_t, (eq. 2) of a contaminant from its point of origin to a sampling point located a distance, ℓ, downstream depends upon the value of ℓ and the ventilation velocity, v_f, within the entry. Clearly, if ℓ is zero, then τ_t is zero and this time need not be considered. (See Design Example II.) However, in many applications, the point of origin of the contaminant may not be known precisely, and sampling locations may have to be distributed in some logical fashion in order to protect an entry (or entries) from a potential hazard. If, for instance, an entry is to be protected from a hazard (such as fire), and the point of origin of the associated contaminants could be any point along the entry, the sampling points should be spaced at some regular interval along the entry. If the entry length is ℓ_E, then for n tubes, the spacing between sampling tubes, ℓ_D, will be given by

$$\ell_D = \ell_E/_n, \tag{6}$$

and the maximum transport time would be one spacing divided by the ventilation velocity, or

$$\tau_t = \frac{\ell_E}{nv_f}. \tag{7}$$

TUBE TRAVELTIME, τ_ℓ

The tube traveltime, τ_ℓ, given by equation 3, depends not only upon the tube length and diameter but also upon the capacity of the pumps used to provide flow through the tube. The volumetric flow rate, Q_v, necessary to provide a

traveltime, τ_ℓ, is the tube volume divided by the tube traveltime; that is,

$$\dot{Q}_v = \frac{\frac{100\pi d_o^2}{4}\ell_o}{\tau_\ell} \qquad (8)$$

with ℓ_o in m, d_o in cm, τ_ℓ in seconds, and $\dot{Q}_v$ in cm^3/s. Substituting τ_ℓ from equation 3 yields

$$\dot{Q}_v = 225\ d_o. \qquad (9)$$

$\dot{Q}_v$ corresponds to the volumetric flow for which the Reynolds number is ~1,800.

Now, for a tube of length, ℓ_o, and inside diameter, d_o, the required pressure drop across that tube necessary to provide a traveltime, τ_ℓ, can be shown to be[3]

$$\Delta P = P_A - P_t = 0.076\ \frac{\ell_o^2}{d_o^2}\ \frac{1}{\tau_\ell} \qquad (10)$$

where P_A = ambient atmospheric pressure at the open end of the tube, assumed equal to 760 mm Hg (1 atm)

and P_t = pressure at the end of the tube just before entering the pumps (mm Hg)

The capacity of the pumps used must be capable of providing the flow, $\dot{Q}_v$ (eq. 9), at the pressure drop, ΔP (eq. 10). In general, the small vacuum pumps used in these systems have free air capacities ranging from 236 cm^3/s (0.5 ft^3/min) to 7.1×10^3 cm^3/s (15 $ft^3/$ min), and are capable of continuous operation at pressure drops across the pump of 580 to 680 mm Hg. Such pumps show a linear decrease in flow rate with pressure drop, ΔP, across the pump. Some typical pump curves are shown in figure 4, illustrating this linear dependence on ΔP. These curves can be represented by the general expression

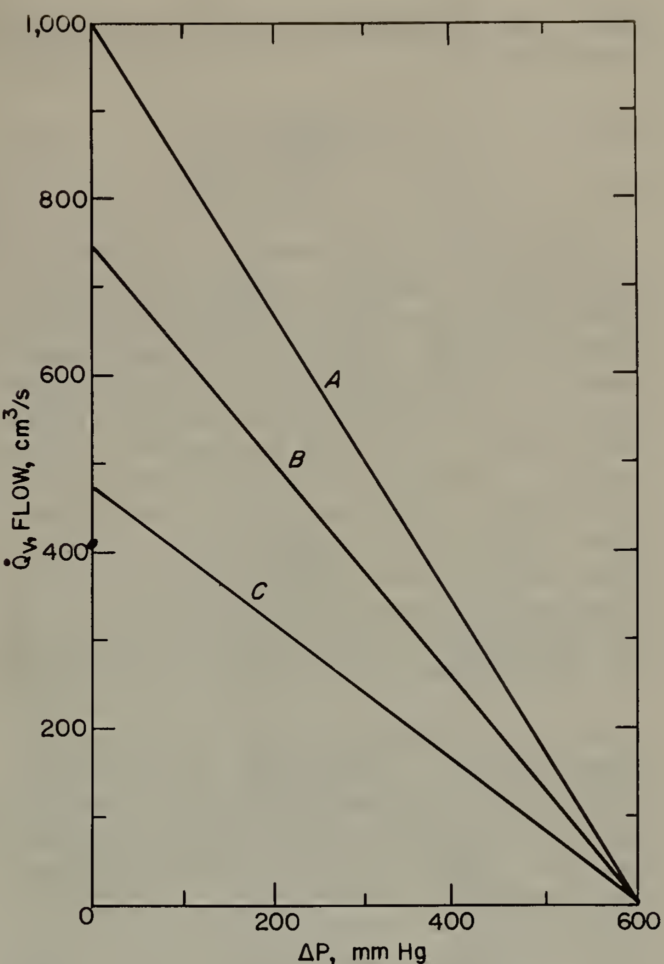

FIGURE 4. - Characteristic flows for three small vacuum pumps as a function of the pressure drop across the pump.

$$\dot{Q}_v = \dot{Q}_o\left(1 - \frac{\Delta P}{\Delta P_m}\right) \qquad (11)$$

Where $\dot{Q}_o$ = free air capacity (cm^3/s) of the pump, and ΔP_m = maximum pressure drop the pump can provide (mm Hg). Assuming the exhaust of the pump to be at atmospheric pressure, the pressure drop across the pump equals the pressure drop across the tube. By substituting the appropriate expressions for $\dot{Q}_v$, ΔP, and τ_ℓ, the required pump characteristics, $\dot{Q}_o$ and

[3]Hertzberg, M., and C. D. Litton. Multipoint Detection of Products of Combustion With Tube Bundles. Transit Times, Transmissions of Submicrometer Particulates, and General Applicability. BuMines RI 8171, 1976, 40 pp.

ΔP_m, can be determined. The resulting expression is

$$\dot{Q}_o > \frac{225\ d_o}{1 - \frac{0.22}{\Delta P_m}\frac{\ell_o}{d_o^3}} \qquad (12)$$

Equation 12 represents an explicit statement of the pump characteristics, $\dot{Q}_o$ (free air capacity), and ΔP_m (maximum pressure drop), necessary for a tube of length ℓ_o, in meters, and inside diameter, d_o, in centimeters, such that the traveltime, τ_ℓ, can be expressed by equation 3. Equation 12 should be used for determining the flow using the maximum tube length of a system, and is applicable only to flow through a single tube. Consequently, equation 12 should be used for determining the sample pump required for the system.

Now, the scavenger pump must continuously purge all tubes except for one. Since it is required that the volumetric flow rate through all tubes be the same, then the capacity of the scavenger pump must satisfy

$$\dot{Q}_{SCAV} > (n-1)\ \dot{Q}_o \qquad (13)$$

where n is the total number of tubes in the system.

Equations 12 and 13 are important design criteria for selection of pumps that are to be used in pneumatic monitoring systems for which the time response is crucial to the overall performance of the system. And, when pumps are used which satisfy these requirements, the tube traveltime of equation 3 can be used directly to determine the τ_ℓ-component of the overall system response time.

Equation 12 also provides a convenient means for determining the maximum length of a given tubing of inside diameter, d_o. As the denominator of equation 12 approaches zero, the required pump capacity, $\dot{Q}_o$, approaches infinity. By setting the denominator equal to zero, the maximum tube length as a function of inside tube diameter can be determined as

$$\ell_o^{MAX} = 4.55\ \Delta P_m d_o^3 \qquad (14)$$

In practice, it is recommended that the maximum tube length not exceed 90% of this value in order to minimize pump requirements. Then, the maximum recommended tube length is

$$(\ell_o^{MAX})_{REC} < 4.1\ \Delta P_m\ d_o^3 \qquad (15)$$

Figure 5 is a plot of $(\ell_o^{MAX})_{REC}$ versus d_o for an assumed ΔP_m of 580 mm Hg.

Using tube lengths in excess of their recommended lengths does not mean that flow through the tubes will cease. Flow will still occur, but at a much-reduced rate, resulting in longer tube traveltimes. Further, when using these longer

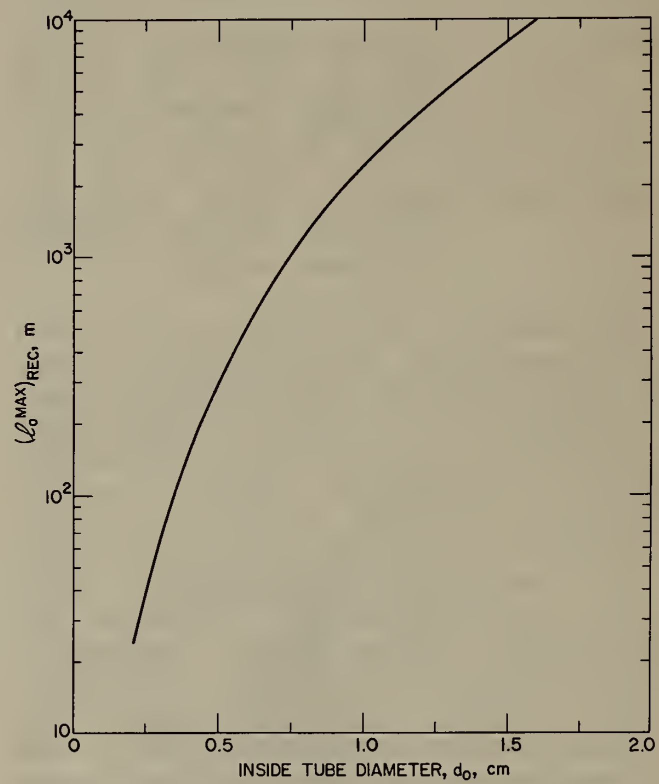

FIGURE 5. - Maximum recommended tube lengths as a function of tube inside diameter for use in pneumatic monitoring systems.

lengths, it becomes difficult to determine, in advance, what the values of these traveltimes will be, and equation 3 is no longer valid for these cases. In general, then, tube lengths greater than their recommended lengths should be used primarily in applications where the time response of the system is not crucial to its performance. Such applications might include the monitoring for spontaneous combustion, or the monitoring of sealed areas within a mine. For this type of application, the tube traveltimes can be measured and the time response of the system can usually be determined, even though it may not be crucial to the overall intended purpose of the system.

SYSTEM SEQUENCE TIME, τ_{SEQ}

For a pneumatic monitoring system composed of n tubes, the time to sequence from one tube through the remaining tubes and back to the original tube is given by equation 4. This time is determined by the number of tubes, n, and the sampling time per tube, τ_{SAMP}. The sampling time per tube can be determined from a knowledge of the response times of the contaminant sensors, and the time required to purge the tubing that connects the sample pump to the contaminant sensors.

Generally, contaminant sensors are connected via a "TEE" connection to the exhaust line of the sample pump (see figure 2), with each sensor requiring a flow of 1 to 2 L/min. As a general rule, the purge time between samples from different tubes should be the time necessary to displace approximately 6 times the volume of the connecting tubing. The total flow rate through the exhaust of the sample pump will equal the flow rate, $\dot{Q}_v$, previously discussed. If the length of tubing, ℓ_m, in centimeters, from the sample pump to the last "TEE" connector to the contaminant sensors is known, and the inside tube diameter is known, then this purge time is

$$\tau_p^M = \frac{\pi d_m{}^2 \ell_m}{4\dot{Q}_v} \times 6 \qquad (16)$$

where the superscript "M" refers to the main exhaust line of the sample pump.

Once the sample of gas reaches the "TEE" connector, it flows to the contaminant sensor at a reduced rate, $\dot{Q}_s$, determined by the flow requirements of the sensor. This sensor purge time is given by

$$\tau_p^s = \frac{\pi d_s{}^2 \ell_s}{4\dot{Q}_s} \times 6 \qquad (17)$$

where the superscript "s" refers to the contaminant sensor tubing between the "TEE" connector and the sensor.

In general, the sensor purge time is much greater than the purge time for the main sample exhaust so that in calculating purge times equation 17 need only be considered. This purge time can be reduced by using small lengths of tubing to connect the contaminant sensors to the sample pump exhaust, and by using smaller diameter tubing. Common 0.318-cm-OD (1/4-in-OD) tubing with a 0.43-cm-ID is recommended.

Also, if the maximum response time, τ_R, of the contaminant sensors is known, then the interconnecting tubing should be of a length such that the additional purge time is less than about 20% to 25% of this response time. For instance, if the value of τ_R is 60 sec and the required sensor flow is 16.7 cm^3/s (1.0 L/min), then for the above size tubing (0.43-cm-ID), the maximum length of connecting tubing corresponding to 20% of 60 s is calculated from equation 17 to be 230 cm (~7.5 ft). Since, in general, sensors are located very close to the sample

pump, this condition can usually be satisfied with little effort.

Then the total sample time is equal to the purge time plus the sensor response time; that is,

$$\tau_{SAMP} = \tau_p^s + \tau_R. \quad (18)$$

But, since τ_p^s must be less than 25% of τ_R, then the total sample time can be written in terms of the maximum sensor response time:

$$\tau_{SAMP} \cong 1.25\ \tau_R \quad (19)$$

Equation 19 is generally valid for sensors with response times greater than 30 s. If faster sensors are used, then equations 17 and 18 should be used to determine the sample time per tube.

DESIGN EXAMPLES

The preceding sections have discussed the components necessary for fabricating a pneumatic monitoring system and presented guidelines for designing systems with rapid response times. This information can now be used for designing and fabricating pneumatic monitoring systems. In order to illustrate how this information can be used, the following two examples are given. These examples are intended to demonstrate the manner in which pneumatic monitoring systems can be designed to monitor for hazards that develop within a short period of time (~15 to 30 min). Clearly, there exist many other potential hazards which are slower to develop and for which the pneumatic monitoring approach is a viable and cost-effective technique.

DESIGN EXAMPLE I

It is desired to use the intake air from a conveyor belt haulageway to provide additional ventilation at the working coal face. In order to use the belt air for face ventilation, a carbon monoxide (CO) monitoring system with an alarm threshold of 10 ppm above ambient is required along the belt haulageway. The entry cross section is ~9.8 m^2 (7- by 15-ft) and is 1,800 m in length (~5,900 ft). The average ventilation velocity within the entry is 0.76 m/s (150 ft/min). Further, the minimum acceptable alarm time for the CO monitoring system is 15 min (900 s).

The objective, then, is to design a pneumatic CO monitoring system with a maximum response time of 15 min for a belt haulageway 1,800 m long with a ventilation flow of 0.76 m/s.

To begin, a CO sensor must be chosen that is capable of responding at the 10-ppm-CO level and with a well-defined time response. Such a sensor is identified with a response time, τ_R, of 30 s. Then from equation 19, the sample time per tube is

$$\tau_{SAMP} = 37.5 \text{ s}$$

and the total sequence time, from equation 4, will be

$$\tau_{SEQ} = 37.5\ n$$

where the number of sampling tubes, n, is yet to be determined.

The second step is to decide upon the location for the control station. One possibility is to locate the control station at the outby side of the belt entry. If this were to be done then the longest sampling tube would be approximately the length of the entry. From figure 5, it can be seen that the required tube diameter is ~0.9 cm (0.35 in) for this maximum length of tubing. If these values for ℓ_0 (1,800 m) and d_0 (0.9 cm) are inserted into equation 3, then it is found that the tube travel time would be 567 s,

which leaves a total time of 333 s remaining for contaminant transport and sequencing time; that is

$$\frac{\ell_E}{nv_f} + 37.5n < 333.$$

If this equation is solved, using the values for ℓ_E and v_f, then it can be shown that no combination of n tubes can satisfy this time requirement. That is, any value of n will yield a total time greater than 333 s. Consequently, the control station must be located at some other point along the belt entry.

For convenience, assume that the control station can be located at the midpoint of the entry. Then the maximum tube length in the system will be 1/2 ℓ_E or 900 m. From figure 5, the required tube diameter for this length is ~0.72 cm (0.28 in). This tube diameter is greater than 0.635 cm (1/4 in) but less than 0.953 cm (3/8 in). The closest standard size tubing that can be used is 0.794 cm (5/16 in). Substituting these values into equation 3 yields a maximum tube travel time of 250 s, which leaves a total time of 650 s remaining for contaminant transport and tube sequencing; that is,

$$\frac{\ell_E}{nv_f} + 37.5n < 650$$

Substituting the appropriate values for ℓ_E and v_f, and rearranging yields

$$37.5n^2 - 650n + 2,368 = 0$$

Solving this equation for n indicates that when 5.2 < n < 12.1, the contaminant travel time plus the tube sequencing time will be less than 650 s. Consequently, the minimum number of sampling tubes which can be used is 6. Setting n=6, the following time components of the system result:

Contaminant Transport Time

$$\tau_t = \frac{\ell_E}{nv_f} = 395 \text{ s}$$

Tube Travel Time

$$\tau_\ell = 0.35 \frac{\ell_E}{nv_f} d_o = 250 \text{ s}$$

Tube Sequence Time

$$\tau_{SEQ} = 37.5n = 225 \text{ s}$$

The maximum system response time is

$$\tau_s = \tau_t + \tau_\ell + \tau_{SEQ} = 870 \text{ s}$$

which is less than the required response time of 15 min (900 sec).

Now, in order to select pumps to satisfy the tube travel time constraint, equation 12 indicates that, for a pump with a maximum ΔP_m of 580 mm Hg (23 in Hg), its free air capacity must be greater than or equal to 562 cm^3/s (~1.2 ft^3/min); and equation 13 indicates that the free air capacity of the scavenger pump must be $\geq 2.81 \times 10^3$ cm^3/s (~6.0 ft^3/min). Since, in general, pumps with these capacities are readily available, no problems are anticipated with regard to selection of pumps for this system.

It should be noted that locating the control station at the midpoint of the haulageway does not represent the *optimum* location. The optimum location is that location which is central with respect to the number of sampling locations. In this case, the maximum tube length is given by

$$\ell_{MAX} = 1/2 \left(\ell_E - \frac{\ell_E}{n}\right) = \frac{n-1}{2n} \ell_E$$

and the total system response becomes

$$\tau_s = \frac{\ell_E}{nv_f} + 0.35 \left(\frac{n-1}{2n}\right) \ell_E d_o + 37.5n.$$

Now, to satisfy the time response requirement, n must be >3. That is, if n is ≤3, then the contaminant transport time plus the sequencing time exceeds 900 s. Further, for n≥4, the maximum tube length will be between 675 m and

900 m, and the closest standard size tubing that can be used for these lengths is 0.794 cm (5/16 in). For n=4, the system response time (from the above equation) would be 930 s, which is too slow. However, when n=5, the system response time becomes 861 s, which is less than the required 900 s. Now, when n=5, the maximum tube length for a central control station is 720 m, and from equation 12, assuming ΔP_m=580 mm Hg, the sample pump capacity required is 393 cm^3/s (~0.84 ft^3/min); and for the scavenger pump, 1.57×10^3 cm^3/s (~3.4 ft^3/min).

Consequently, by locating the control station centrally with respect to the sampling tube locations, the number of tubes needed is five, rather than the necessary six if the control station were located at the midpoint of the belt entry. Also, this location would result in lower pump capacity requirements. While it is clear that the six-tube system would satisfy the time constraints for this application, the centrally located, five-tube system represents the optimum configuration.

With the optimum five-tube system, there will be two tube lengths equal to 720 m and 0.794-cm-ID tubing will be used. There will also be two tube lengths of 360 m each. Referring to figure 5, it can be seen that for these two sampling tubes, 0.635-cm (1/4-in) ID tubing will suffice. The fifth sampling tube is located at, or very near, the control station, so that even smaller tubing could be used if desired.

For this situation, the pneumatic CO monitoring system can be defined as follows:

1. Five sampling tubes located at 360-m intervals along the belt entry, and connected to

2. A control station located 1,080 m (~3,540 ft) inby the belt drive.

3. Each sampling tube will require an end-of-line dust filter at the sampling location and a water trap at the control station. Flame arrestors in each sample line are also recommended.

4. A local alarm shall be provided at the control station and provision made for a second remote alarm at the belt drive or other appropriate location.

5. The sample pump used will require a capacity of ~393 cm^3/s (0.84 ft^3/min); and the scavenger pump, a capacity of 1.57×10^3 cm^3/s (3.4 ft^3/min).

6. Five three-way solenoid valves with associated sequencing controls are required.

7. A CO sensor with an alarm threshold of 10 ppm CO above ambient and a 30-sec response time will be used.

8. If desired, data can be acquired on a continuous basis via a strip-chart recorder or some other type of data acquisition system.

A conceptual layout of the sampling locations and control station for this belt entry is shown in figure 6.

Before concluding this example, it is worth noting that an electronic system could also be designed for this application. Such a system would require three individual CO sensors spaced at intervals of 600 m (1,970 ft), with each sensor hard-wired to a remote control station. Assuming each sensor to have a time response of 30 s, then the maximum response time for this system is the contaminant transport time plus the sensor response time, or 820 s. This system's response time is ~40 s less than the response time of the pneumatic system.

DESIGN EXAMPLE II

Return airways from three working coal faces meet at a common point and air flows outside via a single, common return. Return airway 1 (A1) is 1,600 m (~1.0 mi) long with a ventilation velocity of 0.64 m/s (125 ft/min); the second return (A2) is 2,600 m (~1.6 mi) long with a ventilation velocity of 1.02 m/s

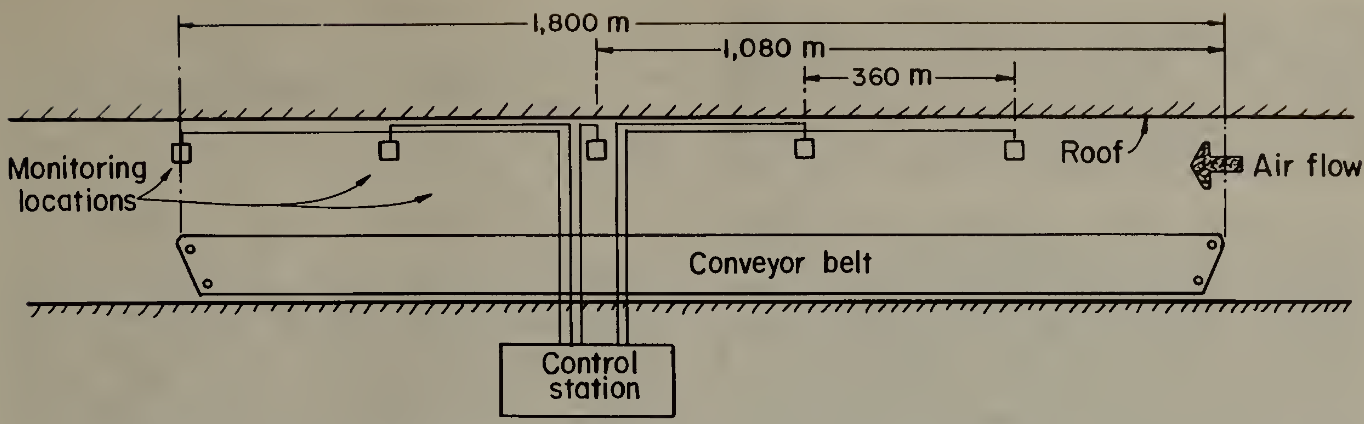

FIGURE 6. - Schematic showing the relative locations of the sampling tubes and control station for the belt entry discussed in Design Example I.

(200 ft/min); and the third return (A3) is 2,500 m (~1.55 mi) long with a ventilation velocity of 0.89 m/s (175 ft/min). The length of the common return is 1,600 m (~1.0 mi) with a ventilation velocity of 2.55 m/s (500 ft/min).

Under normal conditions, the methane content in each of the returns is less than 0.1%. However, the coal seam is beginning to dip, and it is feared that higher methane concentrations may be encountered; this would necessitate ventilation changes and could substantially increase the potential for methane-air explosions. Further, each return consists of extensive abandoned, mined-out areas, and there is legitimate concern about the tendency of spontaneous fires to develop within these areas.

A continuous monitoring system is desired that is capable of providing an alarm should the methane content in a return exceed 0.5%, or should a spontaneous fire occur. The system must be capable of continuous monitoring for methane (CH_4) in the 0% to 1% range, with an alarm at methane levels ≥0.5%, and must also be capable of monitoring for methane in the 0% to 15% range once alarm has been given. Also, the maximum response time of the system at the 0.5% CH_4 level should be less than 30 min, so that adequate time is available to correct any problems that may arise.

It has also been decided that a CO sensor with an alarm threshold of 15 ppm CO above ambient and a response time of 30 sec is to be used for the detection of any spontaneous heatings that may occur. However, due to the long development times anticipated for the spontaneous heatings, the system response time could be much greater than 30 min and still be acceptable. Consequently, since both CO and CH_4 will be measured simultaneously, the system must be constrained to meet the 30-min alarm time for methane.

The objective, then, is to design a pneumatic monitoring system that can satisfy all the above constraints. Since a CO sensor has already been identified, then an appropriate methane sensor must be selected. Such a sensor is identified with dual ranges of 0% to 1% and 0% to 15%, and a maximum response time of 40 s. Also, the methane sensor automatically switches to the 0% to 15% range should an alarm at the 0.5% level occur.

Now, since both CO and CH_4 are to be measured, six sampling tubes will be required. Three sampling tubes will be located just inby the three working faces and are to be used primarily for methane measurements, although CO will also be measured simultaneously. Three other sampling tubes will be located just inby the intersection of the three returns and will be used primarily for CO measurements, although methane will also be measured simultaneously. Because the methane sensor has a longer response time, the sampling time per tube will be limited by its response. From equation 19,

the sampling time per tube will be 1.25 × 40 s, or 50 s, and the total sequence time for six tubes (from equation 4) is 6 × 50 s or 300 s; this is one component of the overall system response time.

An intake entry parallels the common return, and it is decided to locate the control station within this entry, such that the distance from the common intersection to the control station is 50 m (~165 ft). The A1 return is the shortest return, and it can be seen from figure 5 that tubing with a diameter greater than 0.93 cm (0.37 in) would be required for this length (~1,650 m). The standard size tubing that meets this requirement is 0.953 cm (3/8 in) ID. For either entry, A2 or A3, the tubing size must be greater than about 1.03 cm (0.41 in). The standard size tubing that meets this requirement is 1.11 cm (7/16 in) ID. For the three primary CO monitoring tubes, their lengths are approximately 60 m (~197 ft), so that these three sampling tubes must have inside diameters >0.26 cm (>0.103 in). It is decided that standard tubing with a 0.635-cm ID (1/4 in ID) will be used for these three tubes.

A determination of the location for the three primary methane sampling tubes must now be made. Since the tube sequencing time is fixed at 300 s, then the total time available for methane transport from the face to the sampling tube, plus the travel time through a tube is 1,500 s (25 min). For any one of the three entries, the total methane transport time is equal to the distance of the sampling point from the face divided by the ventilation velocity within that respective entry. Also, the maximum tube length for an entry is equal to the total entry length plus the 50 m to the control station minus the distance from the face. If the distance from a face to the sampling tube location is denoted by ℓ, in meters, then the respective times for methane transport and tube travel for each entry (eq. 2 + eq. 3) become

For A1,

$$\tau_{A1} = 1.563\ \ell + 0.334\ (1{,}650-\ell)$$

For A2,

$$\tau_{A2} = 0.98\ \ell + 0.389\ (2{,}650-\ell)$$

For A3,

$$\tau_{A3} = 1.124\ \ell + 0.389\ (2{,}550-\ell)$$

When $\ell = 0$, the sampling tubes are located essentially at the face; from the above equations, it can be seen that this situation corresponds to the lowest times. The reason for this is that the samples are traveling through the tube at a velocity much greater than the entry ventilation velocity, so that the resultant travel time is much lower. When the distance of a sampling tube from the face begins to increase, the resultant times begin to increase. Since the maximum time available is 1,500 s, the maximum distances from the face in each entry can be determined by setting the respective times equal to 1,500 s and solving for ℓ for each entry. The results are

$$\ell\ (A1) \leqslant 772\ m$$

$$\ell\ (A2) \leqslant 794\ m$$

$$\ell\ (A3) \leqslant 691\ m$$

So long as the distances of the sampling tubes from the faces are less than the above respective values, the total response time of the system will be less than the required 30 min (1,800 s). It is decided to locate each sampling tube a distance of 50 m inby the face of each of the three returns. Then the maximum system response times, to methane, within each return are

$$\tau_S\ (A1) = 913\ s\ (15.2\ min)$$

$$\tau_S\ (A2) = 1{,}360\ s\ (22.7\ min)$$

$$\tau_S\ (A3) = 1{,}330\ s\ (22.2\ min)$$

and the lengths of tubing required for each entry are

$$\ell_0\ (A1) = 1{,}600\ m$$

$$\ell_0\ (A2) = 2{,}600\ m$$

ℓ_0 (A3) = 2,500 m

The pump requirements for the system will be determined by the flow requirements for the longest tube (2,600 m). From equation 12, assuming a ΔP_m equal to 580 mm Hg, the sample pump must have a capacity >896 cm^3/s (>1.9 ft^3/min). From equation 13, for this six-tube system, the capacity of the scavenger pump must be >4.48 × 10^3 cm^3/s (>9.5 ft^3/min). Since pumps with these capacities are generally available, no problems are anticipated with respect to pump selection.

Then the pneumatic CH_4-CO monitoring system for this application is defined as follows:

1. Two sampling tubes will be placed in both returns A2 and A3 (four total) with one sampling tube of 1.11-cm (7/16-in) ID located 50 m (~164 ft) inby the face, and the second sampling tube of 0.653-cm (1/4-in) ID located 10 m (~33 ft) inby the common intersection.

2. In entry A1, one sampling tube of 0.953-cm (3/8-in) ID will be located 50 m (~165 ft) inby the face and one sampling tube of 0.635-cm (1/4-in) ID will be located 10 m (~33 ft) inby the common intersection.

3. All six sampling tubes will be connected to the control station located in an intake entry approximately 50 m (~164 ft) from the common intersection.

4. Each sampling tube will require an end-of-line dust filter at the sampling location and both a water trap and flame arrestor at the control station in the sampling line just before entering that tube's three-way solenoid valve.

5. Six three-way solenoid valves with associated sequencing controls are required.

6. A CO sensor with an alarm threshold of 15 ppm CO above ambient and a response time of 30 s will be used to measure the CO levels from each return.

7. A methane sensor with an alarm threshold of 0.5% and a response time of 40 s will be used to measure the methane levels from each return. The methane sensor will automatically switch to a 0%-15% range should the 0.5% CH_4 level be reached.

8. Local alarms shall be provided at the control station with provision made for identification of whether the alarm is for CO or CH_4 and also identification of the sampling location producing the alarm. Provision shall also be made for a second, remote alarm with the same identifying feature at another appropriate location.

9. The sample pump used will require a capacity of ~896 cm^3/s (1.9 ft^3/min); and the scavenger pump, a capacity of 4.48 × 10^3 cm^3/s (9.5 ft^3/min).

10. If desired, provision can be made for continuous recording of CO and CH_4 data, either at the control station or at the remote alarm location.

A layout of the planned system is shown in figure 7.

These two examples clearly indicate that pneumatic monitoring systems can be designed to warn of hazards that develop fairly rapidly.

PNEUMATIC MONITORING FOR SUBMICROMETER PARTICLES

Submicrometer ("smoke") particles are one contaminant that can provide the earliest indication of developing fires.[4] However, these particles, when transported through tubes of a finite diameter, diffuse to the walls and hence can be lost completely within a sampling tube if certain precautions concerning tube diameter and tube travel time are not taken. For this reason, pneumatic

[4]Hertzberg, M., C. D. Litton, and R. Garloff. Studies of Incipient Combustion and Its Detection. BuMines RI 8206, 1977, 19 pp.

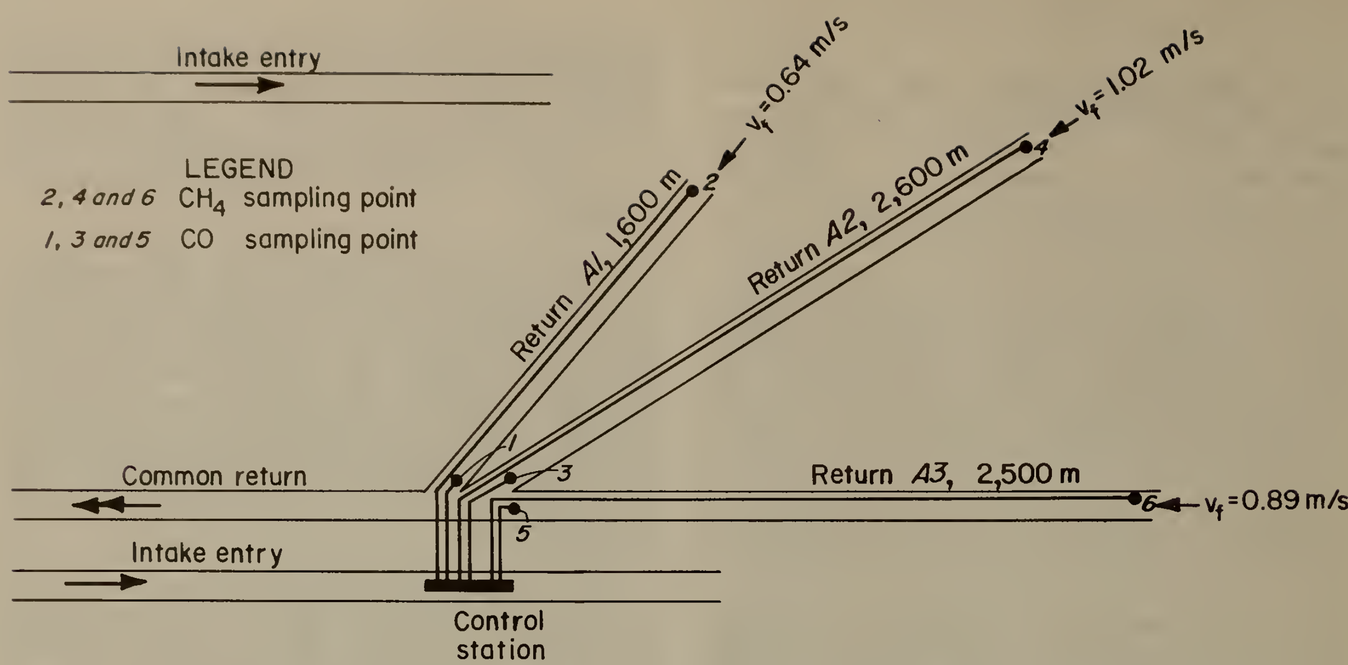

FIGURE 7. - Schematic showing the relative locations of the sampling tubes and control station for the three returns discussed in Design Example II.

monitoring systems designed to measure the concentrations of submicrometer particles have more stringent requirements on tube diameters and tube traveltimes. These additional requirements are presented separately in this section.

For submicrometer particles, it has been found[5] that sufficient constraint for pneumatic sampling is that 25% of all particles with diameters equal to 0.015 μm be transmitted through the longest sampling tube. For laminar flow in a tube (Reynolds number < 1,800), the following relationship must be satisfied in order that this constraint be met:[6]

$$\frac{4D_l \tau_\ell}{d_o^2} < 0.30 \qquad (20)$$

For 0.015-μm particles, the diffusion coefficient, D_l, has a value of 3.3 × 10^{-4} cm^2/s[7], so that the tube traveltime τ_ℓ, must satisfy

$$\tau_\ell < 225\ d_o^2 \qquad (21)$$

[5]Work cited in footnote 4.

[6]Fuchs, N. A. The Mechanics of Aerosols. Pergamon Press Ltd., London, 1964, pp. 184, 204-205.

[7]Work cited in footnote 6.

In order to satisfy both this constraint and the laminar travel time constraint of equation 3, the following relationship between the length and the tube diameter must be met:

$$\ell_o^{SMP} < 640\ d_o \qquad (22)$$

where the superscript "SMP" denotes the maximum tube length for pneumatic sampling of submicrometer particles.

If equation 22 is compared to the maximum recommended tube length (eq. 15), then it can be seen that the ratio is equal to

$$\frac{\ell_o^{SMP}}{(\ell_o^{MAX})_{REC}} = \frac{156}{\Delta P_m d_o^2} \qquad (23)$$

Consequently, when d_o < 0.519 cm, assuming ΔP_m=580 mm Hg, the maximum tube length is limited by the pump capacity and when d_o > 0.519 cm, the maximum tube length is limited by the required transmission of smoke particles. In general, most rapid pneumatic monitoring systems will require standard tubing with >0.635-cm (1/4-in) ID; thus, most particle monitoring systems will have their maximum tube lengths limited by equation 22. For convenience, the maximum tube length as a

function of inside tube diameter is plotted in figure 8, for pneumatic monitoring systems designed specifically for measuring submicrometer particle concentrations.

SUMMARY AND DISCUSSION

In general, there exist two rather broad applications for monitoring systems. One application (category 1) is for hazard detection along an entry (or entries) for which the point of origin of the hazard may not be well defined (for example, see Design Example I). In this type of application, the spacing of sampling points along the entry and the resultant contaminant transport time between sampling points contribute significantly to the overall response time of the system. For a pneumatic monitoring system with the central control station located at the midpoint of the entry, the response times can be estimated from the following equations:

$$\tau_s > 2.1 \left(\frac{\ell_E \tau_{SAMP}}{v_f}\right)^{1/2} + 0.0105\, \ell_E^{4/3} \qquad (24)$$

for contaminant gases; or

$$\tau_s > 2.1 \left(\frac{\ell_E \tau_{SAMP}}{v_f}\right)^{1/2} + 1.44 \times 10^{-4}\, \ell_E^2 \qquad (25)$$

for submicrometer particles.

For instance, from Design Example I (ℓ_E = 1,800 m, τ_{SAMP} = 37.5 s, and v_f = 0.76 m/s), equation 24 would have predicted a system response time of ~856 s. The final calculated system response time for this example was 861 s.

The second type of application (category 2) is for hazard detection when the point of origin of the hazard can be reasonably well defined. In this type of application, monitoring points are located in close proximity to the probable hazard origin so that contaminant transport times can be assumed negligible (for example, see Design Example II). The approximate response time for a pneumatic monitoring system, in this instance, is given by

$$\tau_s > 0.030\, \ell_{MAX}^{4/3} + n\tau_{SAMP} \qquad (26)$$

for contaminant gases; or

$$\tau_s > 6.0 \times 10^{-4}\, \ell_{MAX}^2 + n\tau_{SAMP} \qquad (27)$$

for submicrometer particles.

For instance, in Design Example II, airway A2 (ℓ_{MAX} = 2,650 m, n=6, τ_{SAMP} = 40 s), equation 26 predicts a response time of 1,340 s, while the actual calculated value was 1,360 s for the final design.

These four equations can be used in making initial estimates of pneumatic

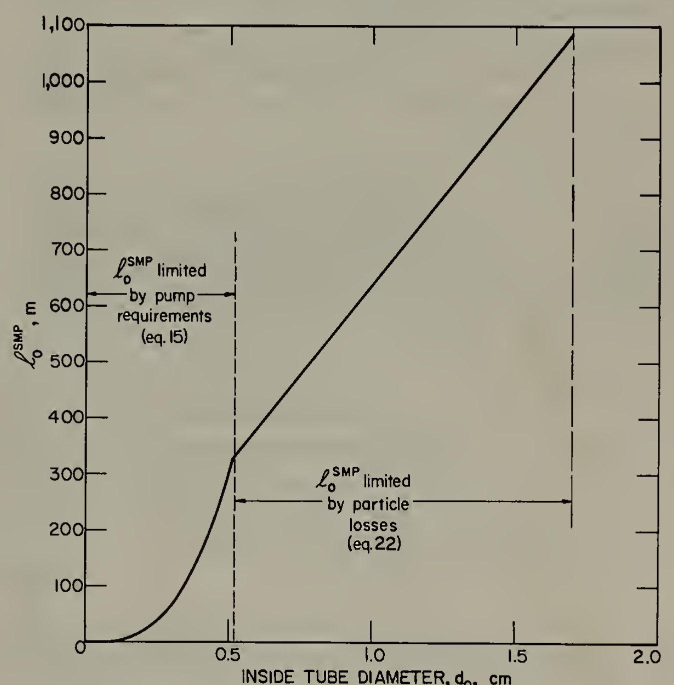

FIGURE 8. - Maximum tube lengths as a function of inside tube diameter for pneumatic monitoring systems designed to detect submicrometer particles.

monitoring system response times to determine if this type of system can be used in a particular application. In general, if the estimated value of τ_s for a proposed application is within ±10% of the required response time, τ_m, or if the estimated value of τ_s is significantly less than τ_m, then a pneumatic monitoring system should be more seriously considered for the proposed application.

In formulating a decision regarding the potential design and fabrication of a pneumatic monitoring system, the following initial questions should be addressed:

1. What is the intended function of the monitoring system?

2. What is the maximum hazard response time, τ_m, that can be tolerated in this application?

3. To which applications category does this application belong?

Category 1--Wide-area coverage for which the point of origin of the hazard is not well defined; or

Category 2--Localized coverage for which the hazard origin is reasonably well defined.

4. If the application belongs in category 1, then for each entry to be monitored, the entry length and average entry ventilation velocity should be specified and used in either equation 24 or equation 25, depending upon whether the contaminant to be monitored is a gas or submicrometer particles, respectively. In utilizing either equation 24 or 25, an average value of τ_{SAMP} = 45 s will generally suffice.

In some instances, an entry may be too long so that a single central control station with associated monitoring points may not provide sufficient time response. In these instances, some thought should be given to subdividing the entry, with each subdivision having its central control station and associated monitoring points.

The example, if a proposed application requires that $\tau_m < 1{,}200$ s (20 min) and the entry is defined by ℓ_E = 4,830 m (3 miles) and v_f = 1.02 m/s (200 ft/min), then τ_s (from eq. 24), would have an estimated value of ~1,830 s (30.5 min), which is considerably longer than the required response time of 1,200 s. However, if the entry is subdivided into two equal lengths (2,415 m each), then two central control stations would be required with each subsystem having an estimated time response of ~1,026 s (17.1 min), which is much less than the required response time of 1,200 s.

Once τ_s has been verified for a proposed category 1 application, then the number of monitoring points required for this application can be estimated from

$$n_{min} \approx \frac{(\tau_m - 0.012\,\ell_E^{4/3}) - \sqrt{(\tau_m - .012\,\ell_E^{4/3})^2 - 4\,\tau_{SAMP}\frac{\ell_E}{v_f}}}{2\tau_{SAMP}} \quad (28)$$

for contaminant gases; or from

$$n_{min} \cong \frac{(\tau_m - 1.6 \times 10^{-4}\,\ell_E^2) - \sqrt{(\tau_m - 1.6 \times 10^{-4}\,\ell_E^2)^2 - 4\,\tau_{SAMP}\frac{\ell_E}{v_f}}}{2\tau_{SAMP}} \quad (29)$$

for submicrometer particles.

n must always be an integer, and for solutions to equation 28 or equation 29, which lie between two integer values, the next largest integer value should always be used for the initial estimate. For a central control station located at the midpoint of the entry (or portion of entry) to be monitored, equation 28 or 29 is a valid and reliable estimate for the number of monitoring points. However, in the final design, it may be possible to reduce n through a more judicious selection of the central control station location.

For instance, applying equation 28 to the application defined in Design Example I (ℓ_E = 1,800 m, v_f = 0.76 m/s, τ_{SAMP} = 37.5 s, τ_m = 900 s), n_{min} has a value of 5.49, or six monitoring points, the value obtained in the example when the central control station was located at the midpoint of the entry. However, in the example, it was found that by centering the central control station with respect to the monitoring point, n could be reduced from 6 to 5.

5. If the application belongs in category 2, then a suitable location should be chosen for the central control station. In general, this location should be central with respect to the monitoring points in order to minimize tube lengths and improve upon system response times. Once the number of monitoring points are defined, the distance from the central control station to the farthest point defines ℓ_{MAX} and either equation 26 or 27 can be used to estimate the system response time relative to τ_m.

Locating the central control station centrally with respect to the monitoring points can have a very significant effect upon the system response time and also reduce the size of tubing required. For instance, if it had been possible in Design Example II to locate the central control station more centrally (in the center of airway 2, for instance), then ℓ_{MAX} would have been ~1,300 m and the estimated response time of the system (from eq. 26) would be ~670 s--almost a factor of 2 more rapid in response. Also, the size of tubing required for the longest sampling tubes would have been reduced from 1.11 cm (7/16 in) to 0.953 cm (3/8 in).

Again, once τ_s has been found to be acceptable for a proposed category 2 application, then more detailed design plans can be initiated. For a category 2 application, the initial minimum number of monitoring points are usually well defined, and additional monitoring points can be added without seriously affecting the original, primary function of the system. For instance, in Design Example II, the system's primary function was to monitor for excessive methane accumulation. The addition of three CO monitoring points increased the response time of the system by only 120 s, yet it now provides for protection from a secondary hazard in addition to providing more information relative to the methane content.

To summarize, a proposed application should be identified as belonging to either category 1 or category 2, and the appropriate equations used for estimating the system response time for the proposed application. If the estimated value for τ_s falls within the limits previously discussed, relative to some required hazard response time, τ_m, then it is reasonable to assume that a pneumatic monitoring system can be successfully implemented for this application.

CONCLUSIONS

The basic components of pneumatic monitoring systems have been described and detailed design criteria presented for rapidly responding pneumatic monitoring systems. The design examples show how this information can be used in the design of such systems. The information contained in this report should be sufficient for designing pneumatic monitoring systems for many potential applications.

APPENDIX.--LIST OF SYMBOLS

D_I	submicrometer particle diffusion coefficient, cm^2/s.
d_m	inside diameter of connecting tubing from sample pump to "TEE" connector, centimeters.
d_o	inside diameter of a pneumatic sampling tube, centimeters.
d_s	inside diameter of tubing connecting the contaminant sensor to the main pump exhaust line, centimeters.
ℓ	distance from point of origin of a contaminant to a downstream pneumatic sampling point, meters.
ℓ_D	the distance between two consecutive pneumatic sampling parts, meters.
ℓ_E	the length of a mine entry, meters.
ℓ_m	the length of tubing connecting the sample pump exhaust to the "TEE" connector, centimeters.
ℓ_{MAX}	the maximum sampling tube length within the pneumatic sampling system, meters.
ℓ_o	the length of a pneumatic sampling tube, meters.
ℓ_o^{MAX}	the maximum sampling tube length, in meters, which can be used with a fixed sampling tube inside diameter, d_o, and a pump with a maximum rated pressure drop, ΔP_m, in mm Hg.
$(\ell_o^{MAX})_{REC}$	the maximum recommended sampling tube length, in meters, for use with a fixed sampling tube inside diameter, d_o, and pump with a rated maximum pressure drop, ΔP_m. $(\ell_o^{MAX})_{REC} = 0.90\ \ell_o^{MAX}$.
ℓ_o^{SMP}	the maximum sampling tube length, in meters, which can be used for pneumatic sampling of submicrometer particles through a sampling tube of inside diameter, d_o.
ℓ_s	the length of tubing connecting the contaminant sensor to the main sample pump exhaust line, centimeters.
n	the number of sampling tubes for a pneumatic sampling system.
n_{min}	the estimated minimum number of sampling tubes required to provide a system response time equal to, or less than, some required, maximum response time.
P_A	atmospheric pressure = 760 mm Hg.
P_t	pressure at the end of a sampling tube prior to entering the sample pump, mm Hg.

ΔP	the difference between P_A and P_t, (P_A-P_t), mm Hg.
ΔP_m	the maximum rated pressure drop for a given pump, mm Hg.
$\dot{Q}_o$	free air capacity of the sample pump, cm^3/s.
$\dot{Q}_s$	flow rate required by a contaminant sensor, cm^3/s.
$\dot{Q}_{SCAV}$	free air capacity of the scavenger, or purge, pump, cm^3/s.
$\dot{Q}_v$	required volumetric flow rate, cm^3/s, through a sampling tube of inside diameter, d_o, and length, ℓ_o.
v_f	ventilation air velocity within a mine entry, m/s.
τ_ℓ	the maximum travel time, seconds, for laminar flow through a tube of inside diameter, d_o, and length, ℓ_o.
τ_m	the maximum anticipated hazard development time, seconds.
τ_p^m	the time required to purge the tubing connecting the sample pump to the "TEE" connector, seconds.
τ_p^s	the time required to purge the tubing connecting the contaminant sensors to the main sample pump exhaust line, seconds.
τ_R	the time response of the contaminant sensor, seconds.
τ_s	the maximum calculated response time for a pneumatic monitoring system, seconds.
τ_{SAMP}	the sampling time per individual sampling tube within the system, seconds.
τ_{SEQ}	the time required to sequence through all of the system's sampling tubes, seconds.
τ_t	the time required for the contaminant to travel in the ventilation flow from its point of origin to a pneumatic sampling point, seconds.